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Physical modelling of cyclically loaded monopiles in sand: the MIDAS centrifuge testing programme

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ABSTRACT: Monopiles are the most common foundation for offshore wind turbines (OWTs), accounting for roughly 80% of installations in Europe. Despite advancements in research, critical knowledge gaps remain, especially regarding the behaviour of monopiles under long-term cyclic loading. Addressing these gaps is vital for enhancing the safety and cost-effectiveness of future offshore wind farms and for assessing the life-cycle conditions of existing OWTs. The "MIDAS: Monopile Improved Design through Advanced Cyclic Soil Modelling" project, conducted in the Netherlands by TU Delft, Deltares, NGI, and industry partners, aimed to fill these gaps. Focusing on sandy soils, MIDAS employed a comprehensive methodology combining experimental (element and centrifuge testing), numerical, and theoretical modelling. This paper presents the centrifuge modelling component, detailing the design and implementation of the testing program, including cyclic load definitions, model pile instrumentation, loading configurations, model seabed preparation, and test procedures. Findings indicate that monotonic responses of monopiles with different configurations can be normalized effectively, validating the quality of experimental outcomes in the context of established theoretical models. The study also explores the impacts of stress levels, monopile dimensions, and drainage conditions on cyclic behaviour, contributing valuable insights to the understanding of monopile-soil interactions under cyclic loads.

Keywords: offshore wind; monopiles; sand; centrifuge testing; cyclic loading

1 INTRODUCTION

Monopiles are the most widely used foundation type for offshore wind turbines (OWTs), accounting for around 80% of OWT installations in Europe. Significant advances and new insights have been achieved through research and industry projects in understanding the behaviour of monopiles as supporting substructures for OWTs. However, there remain substantial knowledge gaps, particularly regarding the response of monopiles under long-term cyclic loading. Addressing these gaps is crucial for improving the safety and economic viability of future offshore wind farms, as well as evaluating the life-cycle health conditions of installed OWTs.

In response to these challenges, a joint industry project (JIP), "MIDAS: Monopile Improved Design through Advanced Cyclic Soil Modelling," was conducted in the Netherlands by TU Delft in collaboration with Deltares and offshore industry partners (Pisanò et al., 2021; Pisanò et al., 2025). The main objective of MIDAS was to advance the fundamental understanding of monopile-soil interaction under cyclic loading, particularly in sandy soils. A comprehensive approach combining experimental (both element and centrifuge testing), numerical, and theoretical modelling was employed in this project.

This paper presents a summary of the technical work related to the centrifuge modelling of monopiles in MIDAS. It provides a summary of the design and execution of the centrifuge testing program, detailing the definition of cyclic loads, the instrumentation of model piles, the loading setup, the preparation of the model seabed, and the execution of the tests. Preliminary results of monopile behaviour under monotonic and cyclic loading in both drained and partially drained are presented, shedding new insights on the diameter effect, cyclic deflection accumulation and drainage condition.

2 PHYSICAL MODELLING

2.1 Geotechnical centrifuge at TU Delft and Deltares

The geotechnical centrifuges at TU Delft and Deltares (as shown in

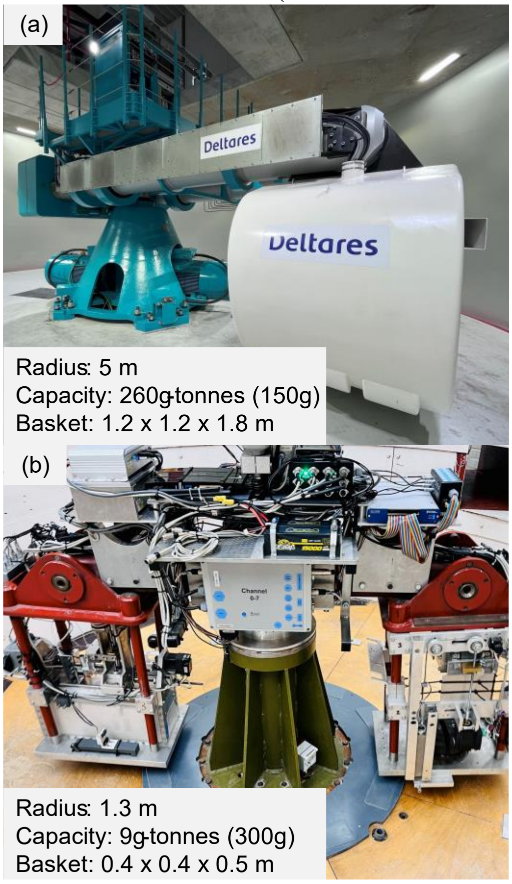

Figure *1*) are the two key facilities adopted to investigate the lateral behaviour of monopiles in sand under monotonic and cyclic loading in the MIDAS project.

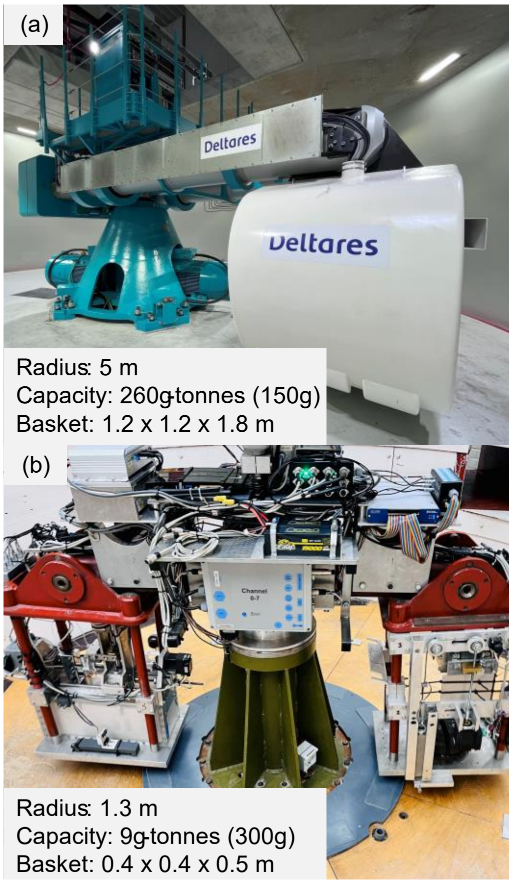

Figure 1 The geotechnical centrifuges at (a): Deltares, (b): TU Delft

The TU Delft centrifuge, a beam type with a 1.22 m radius and a 9 g-ton payload, has been widely used for monopile research (Li, 2020). In comparison, the Deltares centrifuge is significantly larger, with a 5.0 m radius and a 260 g-ton maximum payload. Both are equipped with miniature CPT devices (De Lange et al., 2020) and advanced data logging systems compatible with various measurement sensors (e.g., displacement, force, pressure, strain, and acceleration).

2.2 Testing material and seabed preparation

The Geba sand was used in the MIDAS project. Details of the physical and mechanical properties of the sand, as well as the sample preparation methods are presented in following sections

2.2.1 Geba sand

Geba sand, a sub-angular to sub-rounded sand, has a mean grain size of 0.11 mm with a maximum void ratio of 1.09 and a minimum void ratio of 0.64. Extensively used in the TU Delft geotechnical lab, it supports research applications across pile (Li, 2020) and pipeline (Zhang & Askarinejad, 2019). Additional details of the sand can be found in Zhang & Askarinejad (2019). Addiontally, it should be noted that a minimum (D/d_{50}) of 121 is required for study on laterally loaded piles, i.e., a minimum model pile diameter of 13.3 mm (Klinkvort 2012).

2.2.2 Preparation of sample seabed

At TU Delft, monopile response was tested in two relative densities (D_r) of 40% and 80%, with all tests conducted in dry sand. The seabed preparation involved raining sand to a loose initial state (D_r < 20%) followed by vibration to achieve the target density. At Deltares, tests were performed with relative densities of approximately 60-70% and 90-100% under both dry and saturated conditions. For dry sand of D_r =60-70%, a sand pluviator was used to prepare the model seabed. For denser sand of D_r =90-100%, the seabed was prepared in layers, with sand poured and compacted by tamping. Saturated tests utilized two fluids: water and a high-viscosity fluid (100 times that of water), made from hydroxypropyl methylcellulose (HPMC) solutions. Water saturation was achieved by pluviating sand into water, followed by tamping. For the high-viscosity fluid-saturated seabed, a dry seabed was initially prepared. Vacuum and CO2 flushing were then applied, followed by water saturation from the bottom. Finally, the water-saturated seabed was gradually infused with the high-viscosity fluid through a tank inlet at the bottom.

2.3 Model piles

In the MIDAS project, model piles with diameters of 18 mm, 40 mm, 60 mm, and 80 mm were tested at various centrifuge accelerations, simulating prototype monopiles with diameters from 1.8 m to 12.8 m (Figure 2). Notably, a test conducted in dry sand at Ng can be considered equivalent to the same pile in saturated sand at Ng × G_s/(G_s -1) (G_s is the specific weight of given sand) under drained conditions. This equivalency, validated by Klinkvort (2012), is from the same effective stress distribution along the pile in both cases. The model piles were made of aluminum, with their wall thicknesses designed to match the section bending stiffness of typical monopiles (wall thickness values are presented in Figure 2).

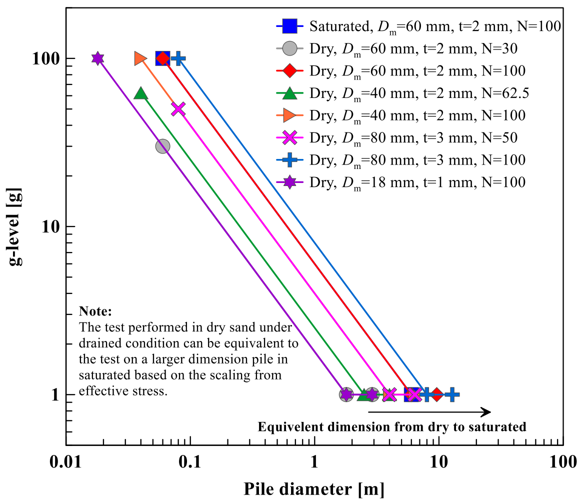

Figure 2 The model and prototype pile diameters in MIDAS

Figure 3 illustrates the pile configurations investigated in this project, showing aspect ratios (L/D, where L is the pile embedded length) and loading eccentricity ratios (h/D, where h is the loading height) ranging from 3.25 to 7.5 and 3.75 to 7.5, respectively. These configurations encompass most monopiles currently used in offshore wind farms as well as those expected for future installations. The model piles were installed by jacking at 1g and wish-in-place for tests at TU Delft and Deltares, respectively.

All the model piles were densely instrumented with strain gauges to measure the bending moments along the pile, which will be used to derive *p-y* curves.

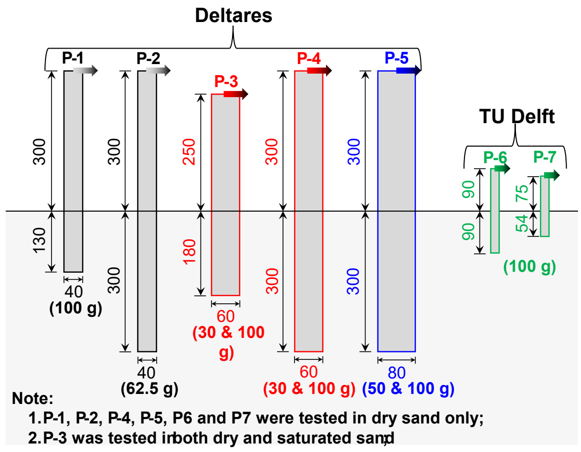

Figure 3 The model pile configurations in MIDAS

2.4 Lateral loading system

Figure 4 shows the loading systems in this project. The TU Delft (Figure 4a) system uses two electric stepper motors to control movement in horizontal and vertical directions, with both displacement-control and load-control modes. A special loading head is designed to simulate a free-head boundary condition.

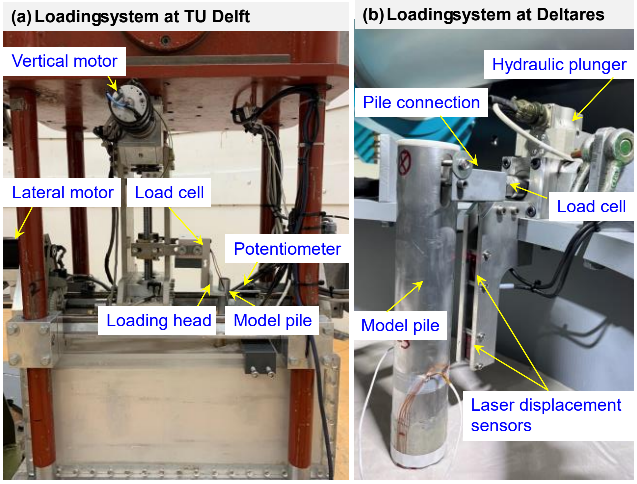

Figure 4 Loading systems at TU Delft and Deltares

The Deltares loading system (Figure 4b) features a servo-controlled hydraulic plunger capable of performing both displacement- and force-controlled tests. Both systems have a load cell and displacement sensor at the loading point to measure force and displacement, providing feedback. Additionally, displacements at two heights above the seabed are recorded to calculate displacement and rotation at the ground surface and provide boundary values for deriving *p-y* curves from bending moment.

2.5 Testing programme

In MIDAS, monotonic tests on different pile configurations and under different seabed conditions were performed first to obtain the capacity of the piles and to investigate the pile-soil interaction. Following the monotonic tests, a series of cyclic tests were performed to study the cyclic lateral behaviour of monopiles in sand. The cyclic load of a typical 14 MW offshore wind turbine was provided by the industry partner, as shown in Figure 5.

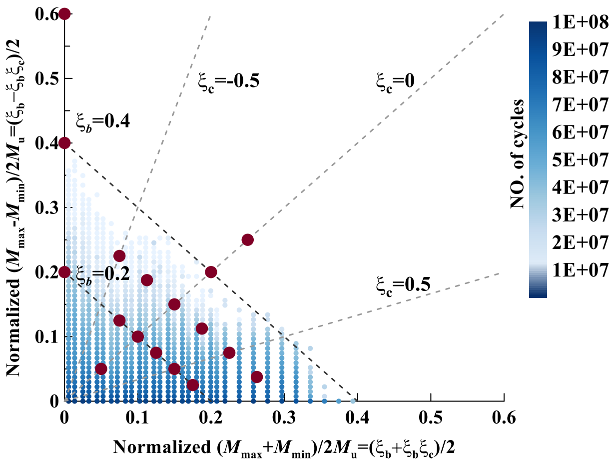

Figure 5 Cyclic loads on a 14 MW turbine and the testing cases in MIDAS

The reference lines defined from load amplitude ratio ($\xi_b = M_{max}/M_u$, where M_{max} is the peak load and M_u is reference capacity defined at 2°) and cyclic ratio ratio ($\xi_c = M_{min}/M_{max}$) in Leblanc et al. (2010) are also plotted in Figure 5. In this case, $\xi_c = 0$ represents a fully one-way loading, i.e., $M_{min} = 0$, while $\xi_c = -1$ represents a fully two-way loading, i.e., $M_{min} = -M_{max}$. In addition, the intercept on y-axis of the line with a slope of -1 has the same ξ_b. As shown in the figure, the cyclic loads on the turbine vary from completely one-way ($\xi_c = 0$) to completely two-way ($\xi_c = -1$), although the peak load is normally less than 40% of the defined reference capacity. In MIDAS, a total of 56 cyclic tests, covering the cyclic load conditions of a typical 14 MW offshore wind turbine, were performed.

3 RESULTS AND DISCUSSION

In this section, some preliminary centrifuge testing results from both monotonic and cyclic tests are presnetd. New insights on the lateral response of monopile in sand are discussed.

3.1 Monotonic lateral behaviour of monopile in drained sand

3.1.1 Unified normalization: diameter

Figure 6 presents the responses of two monotonic tests performed in dry dense sand ($D_r = 95-100\%$) at 100g. The loading rate was 0.1mm/s in all tests. The pile diameters are 6 m and 8 m in prototype dry seabed (i.e., 9.6 m and 12.8 m in prototype saturated sand), while the pile lengths and loading height are 30 m (i.e., *L*/*D*= 5 and 3.75; *h*/*L*=1). The reaction forces of both monopiles increased with rotation, with no plateau capacity observed even at 2° rotation. Given the maximum design rotation of monopile is 0.5°, this highlights that monopile design for offshore wind turbines is governed by small strain stiffness rather than ultimate capacity.